Journal of University of Babylon for Engineering Sciences, Vol. (26), No. (9): 2018.

A Theoretical Study of Some Unsaturated Properties for Different Soils

Mohammed Nawaf Jirjees Alzaidy

Civil engineering Department, Mosul University, Nineveh Province, Iraq

mohammednawaf@yahoo.com

Submission date:- 9/8/2018	Acceptance date:- 7/10/2018	Publication date:- 15/10/2018

Abstract

Soil–water characteristic curves (SWCC) can be defined as the relationship between the water content and suction of an unsaturated soil. It considered a basic relation to explanation of the engineering behaviour of unsaturated soil such as hydraulic conductivity and shear strength, So the study of SWCC is useful to reduce the time and cost of unsaturated soil testing for different engineering purposes. An approach model has been used to predict the SWCC for different soils. The influence of the soils on SWCC shape, the unsaturated hydraulic conductivity and shear strength parameters have been studied in this paper using mathematical models. The results of SWCC show that suction of clay soil is bigger than sandy soil, while the clayey silt soils exhibit an intermediate behaviour at same water content. The values of unsaturated shear strength are increasing while the unsaturated hydraulic conductivity is decreasing with increasing soil suction. This behaviour of the last two parameters with soil suction should be taken in consideration for engineering purposes.

Key words: Unsaturated soil; Hydraulic properties; Shear strength; SWCC.

1. Introduction

Soil water characteristic curve (SWCC) is containing an important information like the water amount in the pores at a limited soil suction and distribution of pore size due to the stress state in the soil. It can be categorized as a function to describe the capacity of water storage of a soil subjected to different suctions. Various properties of unsaturated soil behaviour such as volume change, shear strength, permeability… etc, are related to this curve [1], [2].

Several methods to obtain SWCC is available. There is a direct methods such as pressure membranes, tensiometers, and pressure plate apparatus. These methods measure the pressure of pore water in soil or may be impose a given air pressure to soil and allow equilibrium of water content to be done with the imposed air pressure, However, These experiments are usually costly and time consuming. Therefore, Several empirical methods have been proposed to cope with it. Also a number of alternative analytical methods to predict SWCC depending on the initial index properties of the soils, Such methods is Gene Expression Programming (GEP) which categorized as an artificial intelligence method for modelling of the curve [3].

The hydraulic conductivity function of soils describes the relationship between the unsaturated coefficient of permeability (k_θ) versus soil suction or moisture content, This function is constitutive for the numerical solution of the equations describing flow processes in soils, However, The experimental determination of this function is time consuming and tedious, Therefore great efforts have been invested in developing models to evaluate the function [4]. One of these models is the statistical approaches to determine the unsaturated permeability function using SWCC data and the saturated coefficient of permeability (k_s) of the soil.

The shear strength of a soil is required for addressing numerous problems, i.e. design of foundations, retaining walls, slope stability, and other applications in civil engineering. The shear strength of saturated soil is common and easy to obtain. Assessing shear strength of unsaturated soil, however, is complicated. Several procedures have been found to predict the unsaturated shear strength. These procedures use SWCC as a tool and shear strength parameters of the saturated soil (cohesion c', internal friction angle φ') to predict the unsaturated shear strength function [2].

Johari and Nejad [3] studied the modelling of SWCC using an artificial intelligence method called Gene Expression Programming (GEP). The selected inputs for modelling are the initial void ratio and water content, input suction, clay and silt content. The model output is the gravimetric water content to the assigned input suction. Fredlund *et al.*,[5] studied the predicting of permeability function for unsaturated soils using the corresponding by using a model involves an integration procedure. It also exhibits a significant deviation at low degree of saturation (high suction) range. Leong and Rahardjo [6] suggested another permeability function incorporating the soil suction and a fitting parameter *p* that varies with soil type. Ravichandran and Krishnapillai **[7]** developed a new statistical model for the relative permeability of water in unsaturated soils using the SWCC of the same soil. The model parameters used in the SWCC are used in the relative permeability equation and these parameters are calibrated using SWCC data only. Fattah *et al*., [8] proposed a simple technique for estimating the coefficient of permeability of an unsaturated soil based on physical properties of soils that include grain size analysis, degree of saturation or water content, and porosity of the soil, Also SWCC variables. Fitting methods are applied through the program Soil Vision. Ye *et al*., [9] evaluated a constitutive model for prediction the unsaturated shear strength using the SWCC for weakly expansive soil. They concluded that for engineering purposes, the constitutive model should be carefully selected based on soil properties. Vanapalli *et al*., [2] developed An empirical, analytical model to predict the shear strength in terms of soil suction. The formulation makes use of the SWCC and the saturated shear strength parameters.

The objective of this paper is to observe the influence of the different soils on SWCC variables, the unsaturated permeability function and unsaturated shear strength parameters, Also to observe the effect of soil suction on the unsaturated properties mentioned of the different soils by using predicted models and compare the results to each other.

2. Materials and laboratory tests

2. 1. Study Area

Samples of different soils have been obtained. Four different locations in Nineveh province /Iraq have been clearly selected to represent the soils used in this study. Fig. (1) shows the locations of soil specimens used in this study. CH-soil (36°23′45.3″N, 43°08′11.2″E) and CL1-soil (36°19′01.9″N, 43°12′42.4″E) specimens were collected at north and eastern west in Mosul city respectively. CL2-soil specimens (36°21′05.1″N, 43°22′37.6″E) were collected from Al-Hamdaniya district at east of Mosul city. SM-soil specimens (35°35′00.0″N, 42°44′31.7″E) were collected from Al-Hatra (Al-Hader) district at western south of Mosul city. The soil samples obtained were mostly clay and silt except the last one which was mainly silty sand. Undisturbed soil samples were collected as a block pieces with approximately dimensions (250×250×300) mm at a an average depth of (2 to 4) m below the ground surface for all sites. The samples are sealed immediately with aluminum and nylon containers to keep the water content without change. Disturbed soil samples were also taken and used for index properties such as Atterberg limits, specific gravity, and grain size distribution.

Fig. 1: Locations of soil specimens in Nineveh province

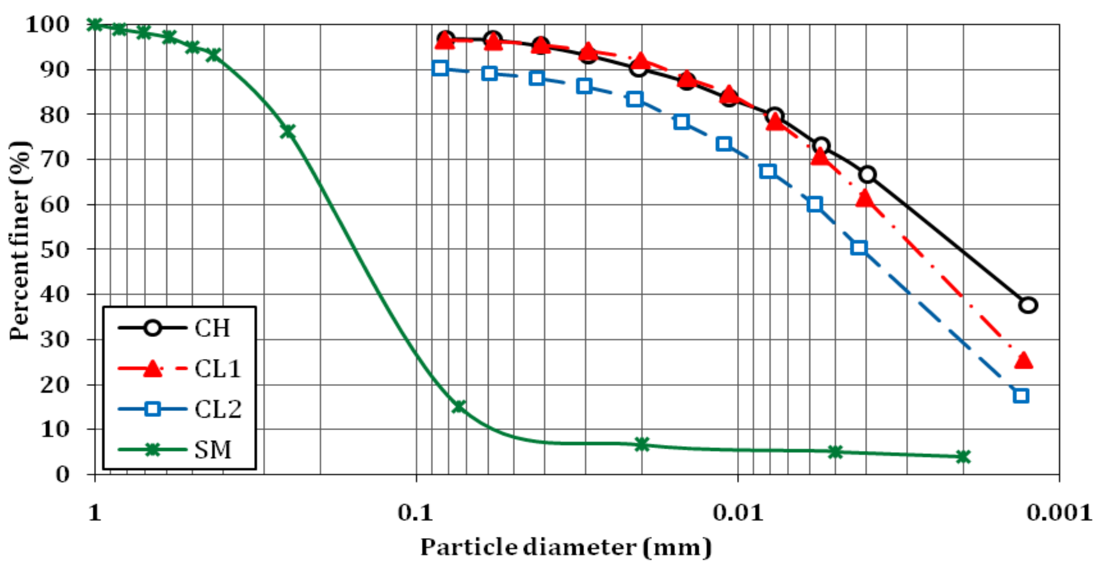


Fig. 2: Grain-size distributions of the soils

Table (1): Properties of the different soils used in the study area

Description		Soil type: CH	CL1	CL2	SM
Specific gravity, G_s		2.71	2.61	2.68	2.64
Initial void ratio, e_o		0.68	0.53	0.59	0.70
Grain size distribution of soils (%)	Gravel	0	0	0	0
	Sand	3	4	10	85
	Silt	48	57	61	11
	Clay	49	39	29	4
Atterberg limits (%)	Liquid limit, w_L	71.1	42.6	31.0	N.P.
	Plastic limit, w_P	36.5	23.7	17.5	N.P.
	Plasticity index, I_P	34.6	18.9	13.5	N.P.
In-situe properties	Water content, w_o (%)	20.0	15.2	17.0	3.5
	Dry unit weight, γ_d (kN/m^3)	15.8	16.2	15.5	17.5
Saturated shear strength parameters	Cohesion, c' (kPa)	28.1	21.4	7.5	0
	Friction angle, φ'°	25.5	26.5	29.7	38.1
Saturated coefficient of permeability, k_s (m/s)		6.5×10^{-9}	3.1×10^{-8}	8.0×10^{-7}	2.3×10^{-5}
Unified Soil Classification System		CH	CL	CL	SM

The index and physical properties of the different soils are listed in table (1). Representative grain-size distribution curves of the soils determined according to ASTM [10] are shown in Fig. (2), Specific gravities of the soils were measured according to the procedure described in ASTM [11], Atterberg limits described in ASTM [12], And the classification of soils following unified soil classification system according to ASTM [13] are also given in the table.

2. 2. Laboratory tests

The following experiments have been conducted on the different soil specimens to evaluate the index and engineering properties:

- ✓ Specific gravity
- ✓ Initial water content and dry density
- ✓ Hydrometer analysis
- ✓ Atterberg limits
- ✓ Direct shear test
- ✓ Permeability test

3. Methods and calculations

3. 1. Soil-water characteristic curve

3. 1. 1. Modeling of soil-water characteristic curve

There are several developed methods to determine the SWCC in geotechnical engineering and soil science. Those different procedures differ in terms of repeatability, accuracy, complexity, ranges of suction (the full range of potential suction values is between 0-10^6 kPa), and most importantly, the cost of experimental methods and the duration required to perform the test [14]. Thus, It is essential to select a theoretical method to predict the SWCC and its variables depending on the initial index properties of the soil.

Several models have been developed to analytically describe the SWCC. The parameters of these models could be defined according to experimental results. The most common models are van Genuchten

[15] and Fredlund and Xing models [16]. Recently Johari and Nejad [3] proposed an analytical approach to modelling the SWCC in unsaturated soils called Gene Expression Programming (GEP), which is a branch of artificial intelligence technique. (GEP) technique is a mathematical relationship depending on the initial index properties of the soil to describe the SWCC of different soils, the inputs model are the initial void ratio e, initial gravimetric water content w, logarithm of suction normalized with respect to atmospheric air pressure Su, clay content Cl, and silt content Si . The output model is the gravimetric water content due to the given input suction which is ranged from 0-105 kPa [3]. (GEP) model have the following form:

$$\mathrm{GWC} = -1/(\mathrm{S_u} + 2\mathrm{Cl} - 2.202\frac{\mathrm{S_u}^4}{\mathrm{Cl}^2} - 7.285) - w[(S_u + 0.062(S_i + e)^2 - 1] \quad (1)$$

In this equation GWC is the predicted gravimetric water content corresponding to the assigned input suction, e, w, Su, Cl, and Si are the initial void ratio, the initial gravimetric water content, the normalized suction logarithm according to atmospheric air pressure (Su=log (suction/100)), the clay content, and the silt content respectively [3].

Afterward, this formula was scaled based on initial water content using equation 2.

$$\mathrm{GWC'} = \mathrm{GWC} \times (\mathrm{w}/\mathrm{GWC_o}) \quad (2)$$

Where:

GWC'= Adjusted gravimetric water content.

GWC= Predicted gravimetric water content.

w = Initial water content.

$\mathrm{GWC_o}$ = Predicted initial water content (at 0.2 kPa).

The procedure used for the proposed model includes the following steps:

a) Choose some value of suctions, beginning from 0.2 (kPa).

b) Normalize the input parameters (e, w, log [su/pa], Cl and Si) using max-min approach.

c) Calculate gravimetric water content at selected suctions using Eq. (1).

d) De-normalize the predicted gravimetric water contents.

e) Adjust the predicted water contents regarding Eq. (2).

f) Draw the SWCC using adjusted water content versus corresponding selected suctions [3].

3. 1. 2. Definition of soil-water characteristic curve variables

Fredlund & Xing [16] indicated that the air-entry value (AEV) is the suction where air starts to enter the largest pores in the soil. The residual water content (θ_r) defined as the water content, which is large suction ranges, is required to reduce additional water from a soil. The values of air entry and the residual state can be determined according to procedure: draw a tangent line at the initial point, second tangent line at the inflection point, and third tangent line at the point where the curve seems to drop linearly in the high suction range, the intersections of mentioned tangent lines give AEV and residual state. The definition of SWCC variables is shown in Fig. 3 [17]. The AEV and residual state are developed in this paper using above definition.

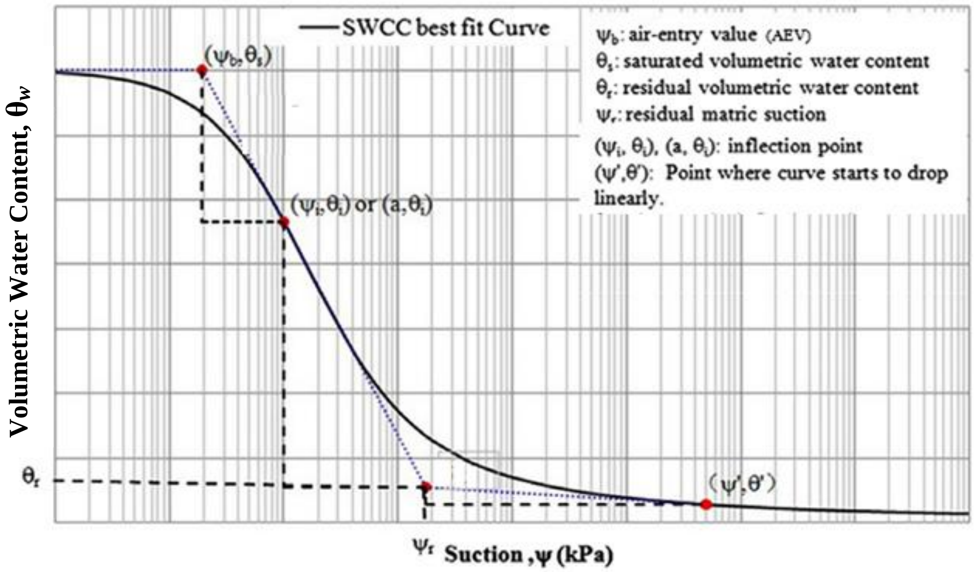


Fig. 3: Soil–water characteristic curve variables [17]

3. 2. Modelling of unsaturated permeability function

Two approaches have been developed to determine the unsaturated permeability functions, Empirical equations and statistical models. Empirical equations are require numerous measured permeability data. A statistical model can be used to predict the permeability functions if the SWCC variables and the saturated coefficient of permeability (k_s), are available.

The saturated permeability (k_s), for the first three soil specimens (CH, CL1 and CL2) have been determined depending the falling head method according to ASTM [18], while the last one (SM) of the soil specimens was measured depending the constant head method according to ASTM [19].

Permeability functions, ($k(\theta_i)$), of the soils have been determined indirectly depends on the statistical model proposed by Kunze [20]. The method uses the saturated permeability function (k_s), and the SWCC variables. The evaluation of each permeability function was done by dividing the SWCC into several equal increments of volumetric water content as stated in [21].

The equation of Kunze [20] is as follows:

$$k(\theta_i)=\frac{k_s}{k_{sc}}\frac{T_s^2\rho_w g}{2\mu_w}\frac{\theta_s^p}{n^2}\sum_{j=i}^{m}\left[(2j+1-2i)\psi_j^{-2}\right]; \qquad i=1, 2, 3, \ldots, m \qquad (3)$$

Where:-

$k(\theta_i)$: predicted coefficient of permeability of volumetric water content θ_i corresponds to the i^{th} interval (m/s),

j: a counter from i to m,

i: interval number that decreases as the volumetric water content increases,

k_{sc}: saturated coefficient of permeability (calculated) (m/s),

k_s: saturated coefficient of permeability (measured) (m/s),

T_s: water surface tension (kN/m),

ρ_w: density of water (kg/m^3),

g: gravitational acceleration (m/s^2),

θ_s: volumetric water content (at saturation),

P: a constant that accounts for the pores interaction of different sizes,

μ_w: water absolute viscosity (N.s/m^2),

m: total number of intervals between the saturated volumetric water content, θ_s, and the lowest volumetric water content,

n: total number of intervals computed between θ_s and θ_w=0 (Note: n=m[θ_s/ θ_s - θ_w], m ≤ n and m = n when θ_w = 0), and

ψ_j: the suction corresponding to the midpoint of the jth interval (kPa).

The water content in SWCC can be established in gravimetric (ω) or volumetric (θ) terms or, alternatively expressed by the degree of saturation (S).

The relationship of SWCC for Kunze (equation 3) should be in term of volumetric water content (θ), so to convert the gravimetric (ω) to volumetric water content (θ) use the following equation:

$$\Theta = \omega \times \frac{\gamma_d}{\gamma_w} \quad (4)$$

Where:

γ_d : dry unit weight of soil, and

γ_w : unit weight of water (9.81 kN/m^3).

3. 3. Modelling of unsaturated shear strength parameters

The shear strength of a saturated soil is usually described using the Mohr Coulomb failure criterion and the effective stress concept, for unsaturated soil, it is described as an extended Mohr Coulomb failure envelope which is considered an extension for the equation of saturated shear strength, the equation of an unsaturated soil as follows [22]:

$$\tau_{ff} = c' + (\sigma_f - u_a)_f \tan\varphi' + (u_a - u_w)\tan\varphi^b \quad (5)$$

Where:-

τ_{ff} : shear stress on failure plane (at failure) (kPa),

c' : intercept of the extended Mohr Coulomb failure envelope on the shear stress axis (the net normal stress and the matric suction at failure = 0) (kPa),

$(\sigma_f - u_a)_f$: net normal stress on failure plane (at failure) (kPa),

u_{af} : pore-air pressure on failure plane (at failure) (kPa),

φ' : internal friction angle associated with the net normal stress state variable (°),

$(u_a - u_w)_f$: matric suction on failure plane (at failure) (kPa) and

φ^b : angle indicating the increasing rate in shear strength relative to the matric suction (°).

The circles of Mohr Coulomb due to failure conditions for an unsaturated soil can be plotted in three dimensional axes, as shown in Fig. 4. The three-dimensional axes have the shear stress, τ, as y-axis, and the two stress state variables, $(\sigma - u_a)$ and $(u_a - u_w)$, as x-axis and z-axis respectively. The plane tangent to the circles of Mohr Coulomb at failure is described as the extended Mohr Coulomb failure envelope for unsaturated soils which is defing as the unsaturated shear strength of soils. The intersection line between the extended Mohr Coulomb failure envelope and the x-y plane is the failure envelope for the saturated condition, (where the matric suction is zero).

The unsaturated shear strength soil can be evaluated using modified triaxial or direct shear equipments. Experimental studies related to the evaluation of the unsaturated shear strength of soils require extensive laboratory facilities and time consuming [23]. In recent years, several semi empirical procedures have been proposed to predict the unsaturated shear strength of soils [2]. The proposed prediction procedures use the saturated shear strength parameters (c', φ') and SWCC data to predict the unsaturated shear strength of soils.

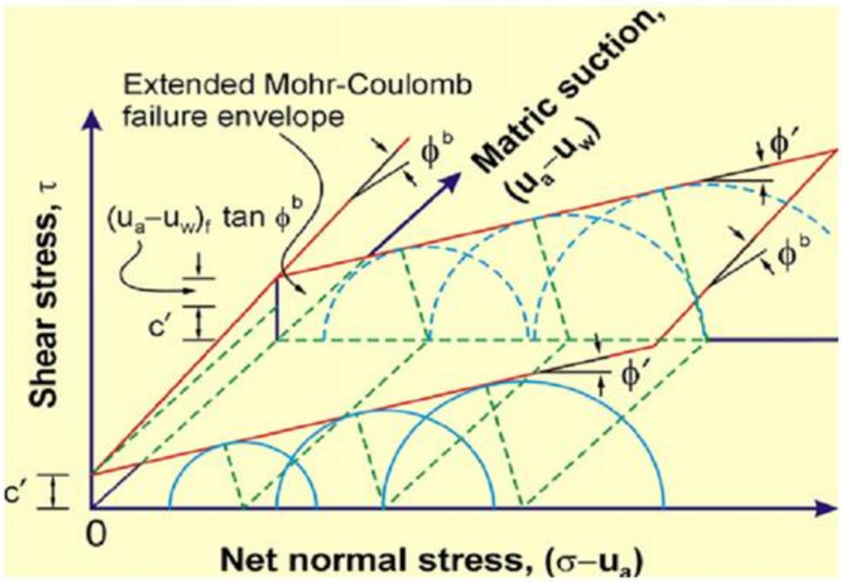


Fig. 4: Extended Mohr Coulomb failure envelope for unsaturated soils [21]

Vanapalli [2] have been proposed a general, nonlinear function to predict the unsaturated shear strength of soil using the entire suction range of SWCC (0 to 10^6 kPa) and the saturated shear strength parameters as shown:

$\tau_{ff} = [c' + (\sigma_f - u_a) \tan\varphi'] + [(u_a - u_w) \Theta^k \tan\varphi']$, Where: (6)

k: fitting parameter used for obtaining a best-fit between the predicted and measured values, it can be determined from fig. (5) which is the relationship between the plasticity index (I_p) of the soil and the parameter (*k*),

Θ: normalized water content, θ_w/θ_s

The shear strength contribution due to suction constitutes the second part of equation, which is: $\tau_{us} = [(u_a - u_w) \Theta^k \tan \varphi']$

Equation (6) can also be written in terms of degree of saturation (S) or gravimetric water content (w), to predict the shear strength yielding similar results.

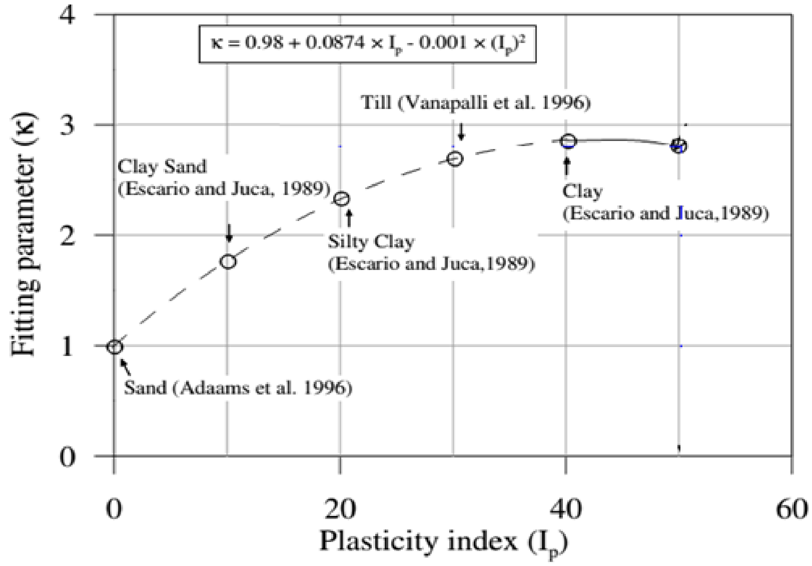


Fig. 5: Fitting parameter (*k*) versus plasticity index [2]

4. Results and discussions

4. 1. Soil-water characteristic curve variables

Equation (1) has been employed to determine the SWCC for studying soils, the results are shown in fig. 6 (a,b and c). It is obvious from the figure that the shape of the SWCC is dependent on soil mineralogy and grain size distribution, which is intrinsically related to pore-size distribution. Their SWCCs have significant differences, the sandy soil (SM) shows a sharp loss of water content for relatively low soil suction values, the clayey soil (CH) shows a more gentle SWCC behavior and the reason lies that clay particles is smaller; surface area increases; number of micro-pore increases. In addition, composition of mineral of the soil also has great influence on soil water characteristic curves. The results of clayey silt soils (CL1 & CL2) exhibit an intermediate behaviour (between SM and CH) and their results were relatively converged. This behaviour agrees with the results of researchers [14] and [21].

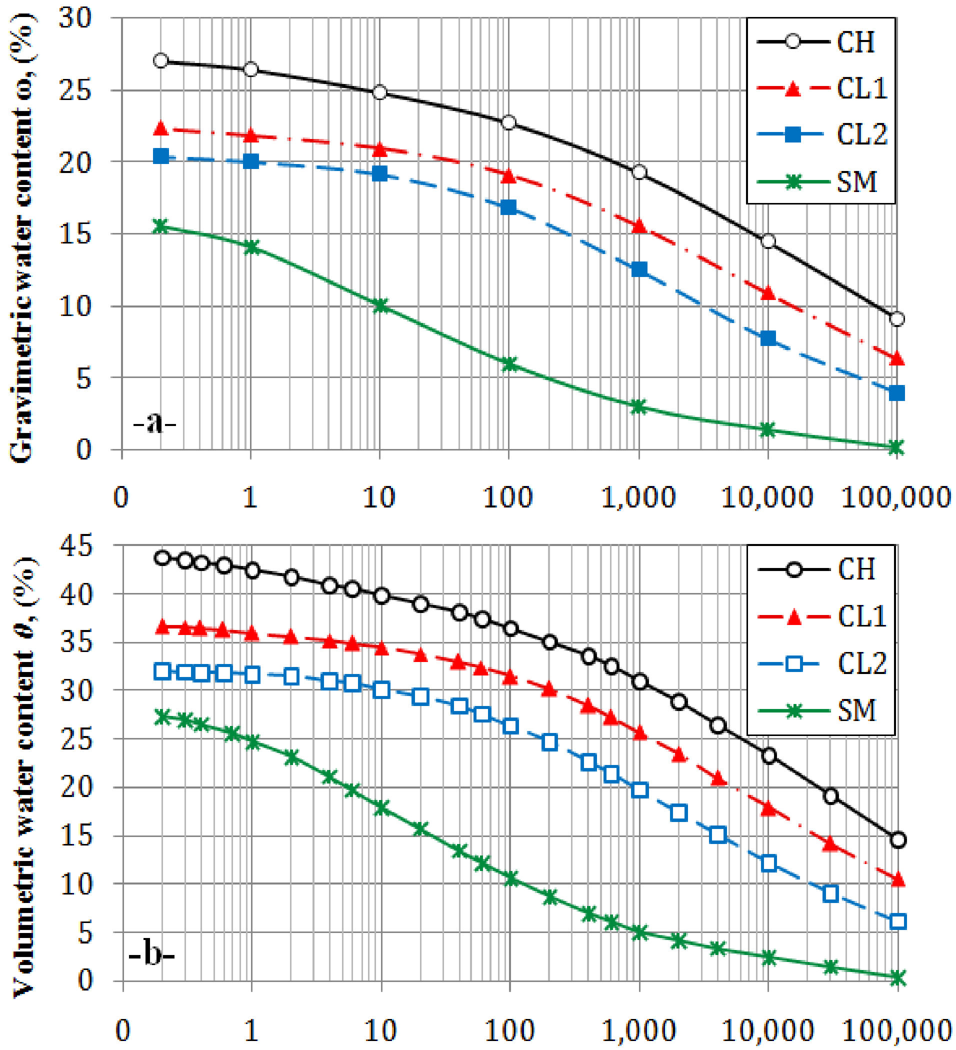
Table 2 shows the SWCC variables represented by Air entry value; the residual state of saturation and related suction of the soils, the coarse-grained soil (SM) has large interconnected pores and shows a tendency to change in gravimetric water content with a fast rate as a value of suction increase. The rate of drying decreases with increase of fine material in the soil. The air entry value is also higher for soils, which have more fine materials. Similarly, the residual state of saturation also increases with the increase in fines. The construction procedure for defining the residual state of saturation appears to be suitable for the all soils except for the very fine-grained soil (CH) which desaturate continuously without exhibiting a distinct break as shown in fig. 6.

Table (2): Soil water characteristic curve variables of the different soils

Variable	Soil type			
	CH	CL1	CL2	SM
Air entry value (AEV), ψ_b (kPa)	220	150	43	0.700
Saturated gravimetric water content, ω_s	0.229	0.198	0.190	0.148
Residual suction, ψ_r (kPa)	30,000	9,000	8,000	400
Residual gravimetric water content, ω_r	0.115	0.108	0.081	0.032

4. 2. Prediction of permeability functions of unsaturated soils

Based on SWCC variables mentioned in table (2) and the saturated coefficient of permeability (k_s), equation (3) was employed to predict the unsaturated permeability functions of the soils. The results of prediction curves for the different soils are presented in fig.7 (a,b and c). The logarithm of unsaturated coefficient of permeability ($k_{(\theta i)}$), versus logarithm of soil suction is shown in fig.(7a). The permeability function can be expressed as a relative coefficient of permeability (k_r), which is the relationship between the unsaturated coefficient of permeability to the saturated one, It can be plotted versus logarithm of soil suction as shown in fig.(7b), It is also possible to plot the data of permeability function as a function of volumetric water content (θ_w), which is shown in fig.(7c). It can be seen generally that there are significant variations in the unsaturated coefficient of permeability ($k_{(\theta i)}$) for the different soils, it is obvious that the steeper curves are for sandy soil (SM), while the clayey soil (CH) showed the lesser effect and had the smoother curves, this is due to the large pores existing in the soil (SM) which exhibited fast draining with increasing values of the soil suction, on contrary the response of clayey soil (CH) was the lesser due to the small pores existing between its particles and the low permeability. The response of clayey silt soils (CL1 & CL2) exhibit intermediate behaviour between the sandy and clayey soil, These results agree with the researchers [24], [25] and [26].



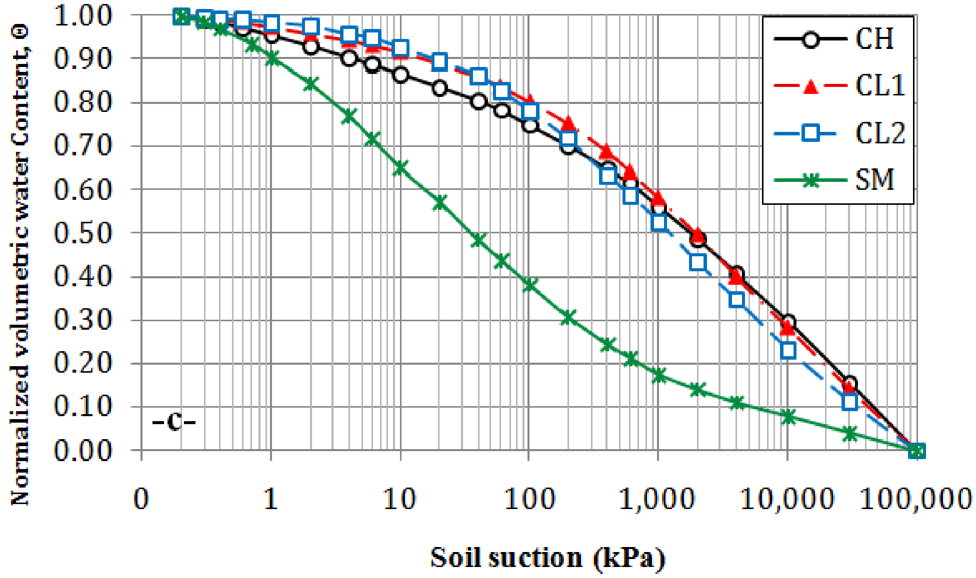
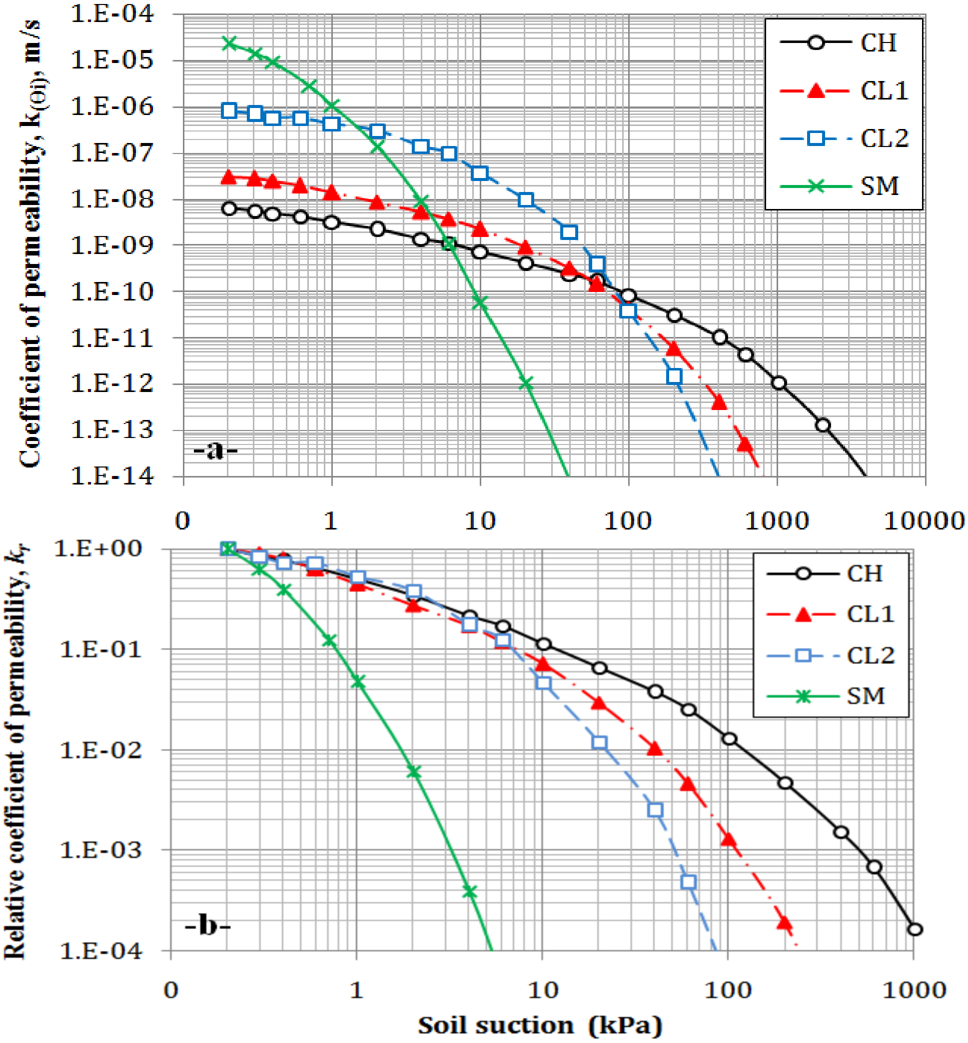


Fig. 6: Soil water characteristic curve of the different soils in terms: a- Gravimetric, b- Volumetric and c- Normalized volumetric water content, versus soil suction



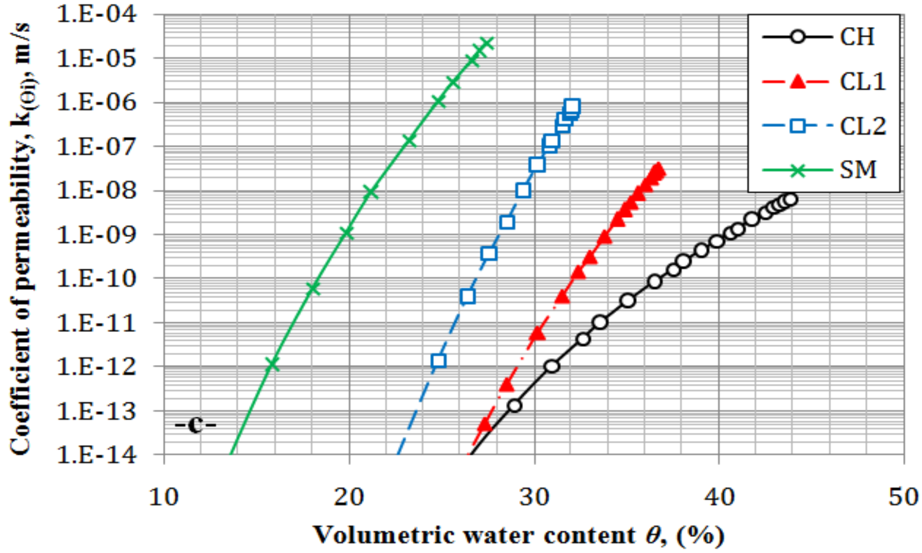


Fig. 7: Unsaturated permeability in terms: a- permeability coeff. $k(_{\theta i})$, b- relative permeability coeff. k_r, versus soil suction, c- permeability coeff. $k(_{\theta i})$ versus volumetric water content, θ

4. 3. Shear strength parameters results

4. 3. 1. Shear strength envelopes of saturated soils

According to the procedure described in ASTM [27], direct shear test (DS) hase been conducted to characterize the shear strength parameters (c', φ') for all types of soils used in this study. DS tests have been carried out on undisturbed soil specimens measuring (60×60×20) mm, the specimens have been consolidated and tested under undrained conditions with a strain rate (0.002) mm/min, the normal stresses ranging from (100 to 300) kPa, the results of the saturated shear strength parameters of the studied soils are shown in table (1) and plotted in fig. 8, the values of effective cohesion (c') ranged from (0-28.1) kPa, while the angle of internal friction (φ') ranged from (25.5°-38.1°), Fig. 8 shows the Mohr Coulomb's peak envelopes for saturated specimens which illustrate the differences in shear strength parameters for the different soils. It is obvious from the figure that the effective cohesion (c') increased with increasing clay content in the soil, in contrary the angle of internal friction decreased with increasing clay content in the soil.

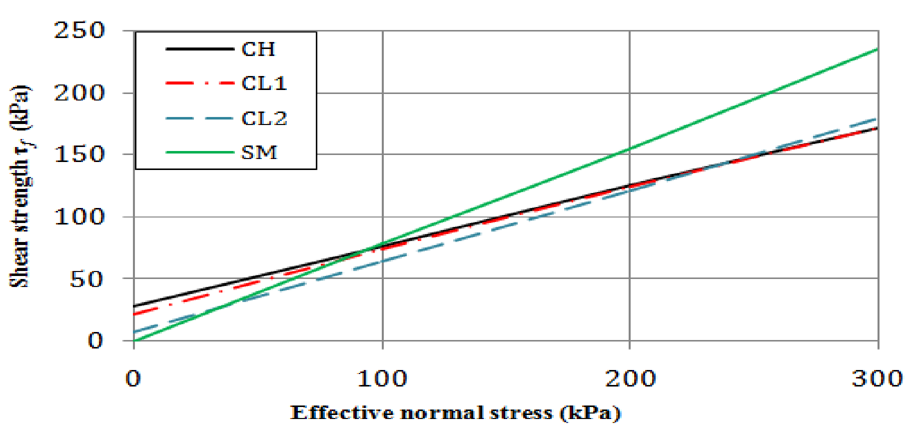
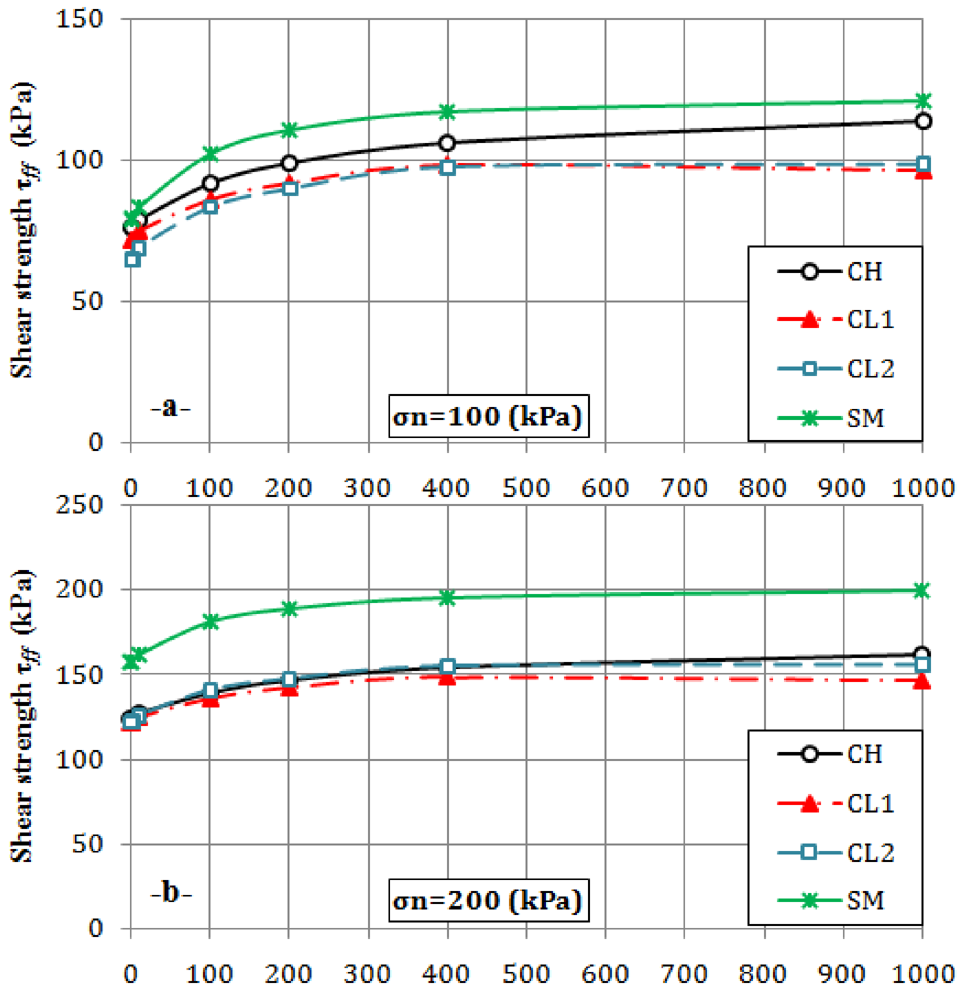


Fig. 8: Mohr Coulomb's failure envelopes of the saturated soils

4. 3. 2. Prediction of shear strength envelopes of unsaturated soils

Based on SWCC variables mentioned in table (2) and the saturated shear strength parameters (c', φ') obtained from the direct shear test, equation (6) was employed to predict the unsaturated shear strength of the soils. The results of prediction curves and measured results for the different studied soils are presented in fig. 9 (a, b and c). It is obvious from the figures that the unsaturated shear strength increases non linearly with increasing soil suction for the different soils, This increment is gradually decreased with increasing soil suction, in other words, the unsaturated shear resistance value (φ^b), is gradually decreased with increasing soil suction, and its value in general is less than the angle of internal friction (φ'), for all types of soils. Fig. 10 shows the variation of the unsaturated shear resistance value (φ^b), for a limited soil suction range of (0-1000) kPa, The value is gradually decreased from the angle of internal friction (φ'), (at zero soil suction) to be approximately zero at (1000) kPa soil suction. This results agree with the results of researchers [28], [29] and [30].



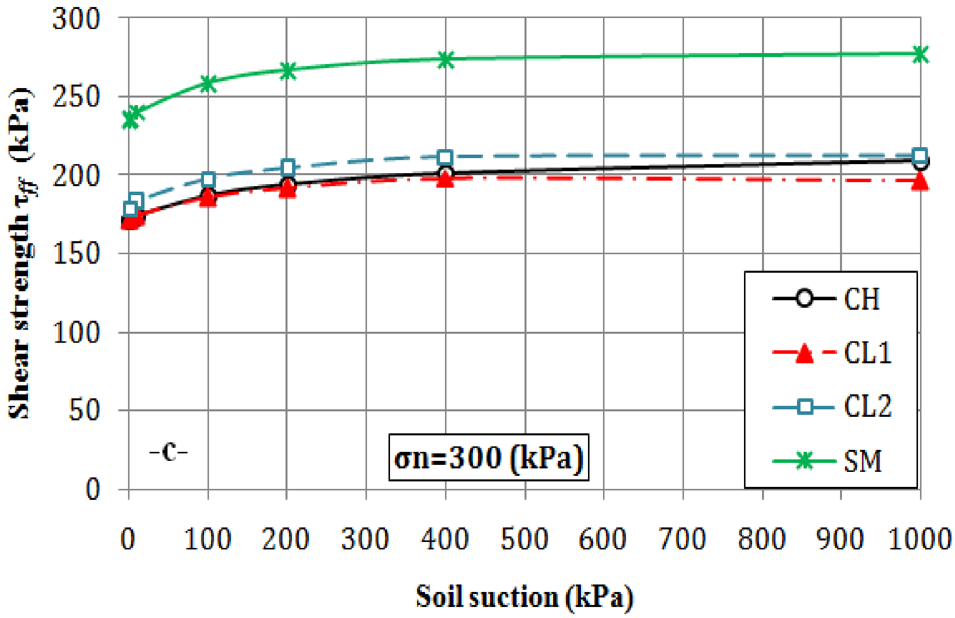


Fig. 9: Unsaturated shear strength τ_{ff} at different normal stress: a- σ_n=100 (kPa), b- σ_n=200 (kPa), and c- σ_n=300 (kPa), versus soil suction

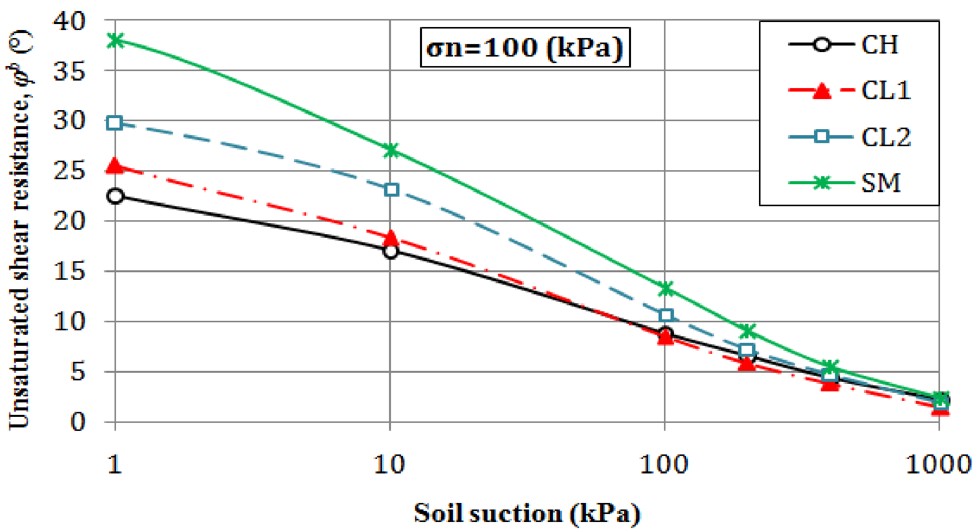


Fig. 10: Unsaturated shear resistance, φ^b at normal stress, σ_n=100 (kPa), versus soil suction

5. Conclusions

The soil water characteristic curve is considered very important components to explanation of the engineering behaviour of unsaturated soils. It characterizes the variation of soil suction due to the moisture content change. Various behaviour of unsaturated soil like volume change, hydraulic conductivity, shear strength, and permeability are related to this curve.

In this paper a statistical model have been used for predicting of SWCC using the initial index properties of the soil, afterwards use the SWCC variables and the results of saturated soils for predicting “the unsaturated hydraulic conductivity and unsaturated shear strength” of the different soils using statistical models.

The numerical results using the procedure proposed in this paper to evaluate all of the SWCC, the unsaturated hydraulic conductivity and the unsaturated shear strength for the different soils used in this study show a good agreement with the previous researchers.

The results of SWCC of the different soils show significant differences, the sandy soil (SM) shows a sharp loss of water content for relatively low soil suction values, the clayey soil (CH) shows a more gentle SWCC behavior, while the clayey silt soils (CL1 & CL2) exhibit an intermediate behaviour and their results were relatively converged.

The contribution of the unsaturated shear strength depends on the soil suction and the type of soil. For a particular soil suction and normal stress the value of the unsaturated shear strength was the higher for (CH) soil, while the value was the smaller for (SM) soil, this is due to the large pores existing in the latest soil (SM) which exhibited fast draining with increasing values of the soil suction, So the variation of φ^b for (SM) soil with increasing suction is more steeper comparing with the other soils, and the (CH) soil is the less.

CONFLICT OF INTERESTS.

- There are no conflicts of interest.

References:

[1] Fredlund, D.G., Xing, A., Fredlund, M.D., Barbour, S.L., “The relationship of the unsaturated soil shear strength to the soil–water characteristic curve”, *Canadian Geotechnical Journal*, vol. 32, pp. 440–448, 1995.

[2] Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E., Clifton, A.W., “Model for the prediction of shear strength with respect to soil suction”, *Canadian Geotechnical Journal,* vol. 33, pp. 379–392, 1996.

[3] Johari, A., & Nejad, A. Hooshmand., “Prediction of soil-water characteristics curve using gene expression programming” , *IJST, Transactions of civil engineering,* vol. 39, No. C1, pp. 143–165, 2015.

[4] Assouline, S., “A model for soil relative hydraulic conductivity based on the water retention characteristic curve”, *Water resources research*, vol. 37, no. 2, pp. 265-271, 2001.

[5] Fredlund, D. G., Xing, A., Huang, S., “Predicting the permeability function for unsaturated soils using the soil-water characteristic curve”, *Canadian Geotechnical Journal*, Vol. 31, No. 4, pp. 533-546, 1994.

[6] Leong, E. C., Rahardjo, H., “Permeability functions for unsaturated soils”, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 12, pp. 1118-1126, 1997.

[7] Ravichandran, N., Krishnapillai, S., “A statistical model for the relative hydraulic conductivity of water phase in unsaturated soils”, *International Journal of Geosciences*, Vol. 2, pp. 484-492, Nov. 2011.

[8] Fattah, M. Y., Ahmed, M. D., Ali, N. A., “Prediction of Coefficient of Permeability of Unsaturated Soil”, *Journal of Engineering*, Vol. 20, No. 2, pp. 33-48, Feb. 2014.

[9] Ye, W., Zhang, Y., Chen, B., Zhou, X., Xie, Q., “Shear strength of an unsaturated weakly expansive soil”, *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 2, No. 2, pp. 155–161, May 2010.

[10] ASTM D 422, “Standard test method for particle-size analysis of soils”, 2016.

[11] ASTM D 854, “Standard test methods for specific gravity of soil solids by water pycnometer”, 2014.

[12] ASTM D 4318, “Standard test methods for liquid limit, plastic limit, and plasticity index of soils”, 2017.

[13] ASTM D 2487, “Standard practice for classification of soils for engineering purposes (unified soil classification system)”, 2017.

[14] Nam, S., Gutierrez, M., Diplas, P., Petrie, J., Wayllace, A., Lu, N., Munoz, J. J., “Comparison of testing techniques and models for establishing the SWCC of riverbank soils”, *Engineering Geology*, vol. 110, pp. 1–10, 2009.

[15] Van Genuchten, M.T., “Closed-form equation for predicting the hydraulic conductivity of unsaturated soils”, *Soil Science Society of America Journal*, vol. 44, no. 5, pp. 892–898, 1980.

[16] Fredlund, D.G., Xing A., “Equations for the soil-water characteristic curve”, *Canadian Geotechnical Journal*, vol. 31, pp. 521-546, 1994.

[17] Zhai, Q., Rahardjo, H., “Determination of soil-water characteristics curve variables”, *Computers and Geotechnics*, vol. 42, pp. 37–43, 2012.

[18] ASTM D 5856, “Standard test method for measurement of hydraulic conductivity of porous material using a rigid-wall, compaction-mold permeameter”, 2015.

[19] ASTM D 2434, “Standard test method for permeability of granular soils (constant head)”, 2015.

[20] Kunze, R.J., Uehara, G., Graham, K., “Factors important in the calculation of hydraulic conductivity”, *Proceedings Soil Science Society of America*, vol. 32, pp. 760–765, 1968.

[21] Fredlund, D.G., Rahardjo, H., Fredlund, M.D., *Unsaturated Soil Mechanics in engineering practice*, John Wiley & Sons, Canada, 2012.

[22] Fredlund, D.G., Morgernstern, N.A., Widger, R.A., “The shear strength of unsaturated soils”, *Canadian Geotechnical Journal*, vol. 15, pp. 313–321, 1978.

[23] Gan, K. M., Fredlund, D. G., Rahardjio, H., “Determination of the shear strength parameters of an unsaturated soil using the direct shear test”, *Canadian Geotechnical Journal*, vol. 25, no. 3, pp. 500-510, 1988.

[24] Gonzalez, P. A., Adams, B. J. “Mine tailings disposal: I. Laboratory characterization of tailings”, *Internal Report, Department of Civil Engineering, University of Toronto, Toronto,* pp. 1–14, 1980.

[25] Fredlund, D.G., Xing, A., Huang, S., “Predicting the permeability function for unsaturated soils using the soil-water characteristic curve”, *Canadian Geotechnical journal*, vol. 31, no. 3, pp. 521-532, 1994.

[26] Zhai, Q., Rahardjo, H., “Estimation of permeability function from the soil-water characteristic curve”, *Engineering Geology journal*, vol. 199, pp. 148–156, 2015.

[27] ASTM D 3080, “Standard test method for direct shear test of soils under consolidated drained conditions”, 2011.

[28] Vanapalli, S.K., Lane, J. J., “A simple technique for determining the shear strength of fine-grained soils using the conventional direct shear apparatus”, *2nd Canadian Specialty Conference on Computer Applications in Geotechnique, Canada*, 2002.

[29] Bilotta, E., Cascini, L., Foresta, V., Sorbino, G., “Geotechnical characterisation of pyroclastic soils involved in huge flowslides”, *Geotechnical and Geological Engineering*, vol. 23, pp. 365–402, 2005.

[30] Hadz’i-Nikovic’, G. D., “The influence of the grain-size distribution and soil structure on the unsaturated shear strength of loess sediments in Belgrade”, *central Serbia*, vol. 70, pp. 83-91, 2009.

دراسة نظرية لبعض الخصائص غير المشبعة لترب مختلفة

محمد نواف جرجيس الزيدي

قسم الهندسة المدنية، كلية الهندسة، جامعة الموصل

mohammednawaf@yahoo.com

ألخلاصة

يمكن تعريف منحني خاصية التربة–الماء بأنه العلاقة بين محتوى الرطوبة وإجهاد الامتصاص للتربة غير المشبعة. إن لهذا المنحني علاقة جوهرية أساسيّة في تفسير السلوك الهندسي للترب غير المشبعة، إذ يمكن من خلاله التنبؤ بدوال الترب غير المشبعة مثل التوصيلية الهيدروليكية ومقاومة القص وبالتالي التقليل من الوقت والجهد والكلفة اللازمة لإجراء مثل هذه الفحوصات للأغراض الهندسية المختلفة. تم في هذا البحث استخدام نمذجة رياضية للتنبؤ بمنحني خاصية التربة–الماء لترب مختلفة، وكذلك دراسة تأثير هذه الترب على شكل منحني خاصية التربة–الماء والتوصيلية الهيدروليكية غير المشبعة ومعاملات مقاومة القص بالاعتماد على النّمذجة الرياضية. بينت النتائج لمنحني خاصية التربة–الماء بأن إجهاد الامتصاص للتربة الطينية هو أكبر منه عند التربة الرملية عند ثبات قيمة محتوى الرطوبة، في حين أظهرت الترب الغرينية الحاوية على طين سلوكاً وسطاً. أما فيما يخص مقاومة القص غير المشبعة فقد ازدادت مع زيادة إجهاد الامتصاص للتربة، في حين أظهرت التوصيلية الهيدروليكية سلوكاً مغايراً فقد انخفضت مع زيادة إجهاد الامتصاص للتربة، وبالتالي يجب الأخذ بنظر الاعتبار سلوك هذين العاملين الأخيرين وعلاقتهما مع إجهاد الامتصاص للتربة للأغراض الهندسية.

الكلمات الدّالة: التربة غير المشبعة، الخصائص الهيدروليكية، مقاومة القص، منحني خاصية التربة–الماء.